Analysis of different frost indexes and their potential to assess frost based on HAM simulations

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Abstract. To reach the climate goals of 2020 our buildings have to become a lot more energy-efficient. This challenge rests mainly on the shoulders of the renovation sector because new buildings are only a small part of our building stock. Old buildings mainly cannot get insulated on the outside because the facade is historically valuable or because of urban planning restrictions. In those cases interior insulation or - if possible - cavity insulation are the only options. However, these renovation strategies may induce severe risks for the existing structure. One of the main risks is frost damage: the interior insulation lowers the temperature of the exterior facade and decreases the drying potential to the inside which leads to an increased risk of frost damage. Most of the studies that assess the risk of frost damage struggle with the dependency of the highly variable material properties of the façade. Therefore this paper investigates the potential of new and existing indexes to assess the risk of frost damage based on the output results of HAM simulations.

Introduction

Although the paper of Grossi, Brimblecombe and Harris: “Predicting long term freeze–thaw risks on Europe built heritage and archaeological sites in a changing climate” [1] predicts a lowering of the risk of frost damage in mean climates due to the climate change, the problem of frost damage will always be significant in mild and cold climates [2, 3]. Due to the climate change the amount of precipitation will increase which will cause wetter and on that behalf more vulnerable facades towards frost. To assess the risks that come with insulation interventions on the building envelope HAM models have proven their value but the results highly depend on the used failure criteria and the input parameters [4].

When interior insulation is installed on historic valuable masonry constructions the heat loss through the building envelope to the exterior and the drying potential of the exterior façade decreases which means an increased risk of frost damage. Therefore a lot of research is done on frost damage and several indexes are developed to assess this. These indexes can be summarized in two categories, the ones linked to the material properties of the wall [5, 6] and the ones linked to the climate conditions [4, 7, 8, 9]. Combining both is often very complicated.

HAM software’s have vast databases with all the needed material properties of common materials but these are not always representative enough for a specific case, for example in historic brickwork the material properties can widely vary [10]. Secondly big climate datasets are usually necessary. Often these are not available or too time consuming for simulations therefore test reference years (TRY) [11] are developed. A TRY is one year of data that is defined to represent a large amount of data [12]. The Fuse of TRY’s will suffice in this comparison study.

The most common criterion that combines material properties and climate conditions is the number of frost thaw cycles while the material is critically saturated (FTCs) [5, 8] but even this method has several shortcomings [13, 14, 15].

Therefore this paper will assess the potential of new and existing criteria to define the risk of frost damage based on the output of HAM simulations.

What's behind frost damage?

Several researchers have proposed different physical principles but the two most common explanations for frost damage are the hydrostatic pressure theory and the ice lens mechanism.

Hydrostatic pressure. Water freezes first in the big pores and then water drains from these big pores to smaller surrounding pores due to the volume increase. This water transport causes a friction which results in tensile stress in the surrounding material. This stress can cause cracks at high freezing speeds.

Ice lens mechanism. The damp pressure above ice is lower than above water which ensures that surrounding water vapour is pulled to the ice and frozen. This mechanism makes sure that ice grows starting from the big pores to the surrounding ones. This growing ice can grow to nearby capillaries but to freeze a fine capillary a high pressure is needed. When the material is weak the capillaries will not freeze but they will form a crack under the pressure generated by the surrounding ice. This will form a crack parallel to the surface. The ice lens mechanism causes the most damage by long periods of frost.

As you can see these two mechanisms have different circumstances that trigger the forming of damage but nevertheless will also influence and strengthen each other so they cannot be seen separately.

Most of the researchers agree that the risk of frost damage highly depends on the pore structure and tensile strength of the material. Therefore most of the researchers focus on finding the reliable methods to define all needed material properties: pore size distribution, capillary absorption, tensile strength and so on. For this they use standard methods to define the capillary absorption, over mercury intrusion porosimetry to high-tech methods as dilatometry, water porometry, calorometry and image analysis [16]. But are these tests also necessary to be able to compare different wall assemblies?

Several existing indexes to assess the risk of frost damage

The most common frost indexes are the number of critical frost-thaw cycles [5, 8], the winter index (WI) [11], the time-of-frost (TOF) [17], the surface frost intensity [18], the frost intensity + number of FTC = intensity*sqrt(number of cycles/year), the frost decay exposure index (FDE) [7], the wet frost index (WI) and the length of propagated crack [19]. The first three will be taken into account in this paper.

The **number of critical frost-thaw cycles** (FTCs) is a very common, and easy applicable method as explained above. The method is based on counting the number of freeze thaw cycles while the moisture saturation is above the critical saturation degree. This critical saturation degree is a material dependent constant that specifies the moisture content at which frost damage can occur in proportion to the fully saturated moisture content. This critical moisture content can be experimentally defined by laboratory test due to measuring the Young's modulus during a freezing test for different moisture contents. At a certain moisture content there will be a knick-point value which defines the critical moisture content [20]. Fagerlund has also defined the critical saturation degree (Scr) in function of material properties:

$$S_{CR} = 1 - \frac{1}{\left(1+\alpha\sqrt{\frac{2\sigma_B B(1-P(1-S_e))}{0.09 W_f \, {}^{d\beta}/_{dt}}}\right) P(1-K)} \tag{1}$$

α	Specific surface of air filled pores	m²/m³
σ_B	Tensile strength of material	N/m²
B	Coefficient of permeability (including viscosity of fluid)	m³s/Kg
P	Porosity	m³/m³

S_e	Degree of saturation	-
W_f	Freezable water content at lowest temperature	m³/m³
β	Fraction of W_f actually frozen	-
t	Time	s
K	Non freezable water content at lowest temperature as fraction of pore volume	m³/m³

Unfortunately Straube [10] proved that even for at first sight similar looking building material large deviations in the Scr value are possible, and that the value depends highly on the pore size distribution and tensile strength of the material which makes it difficult to define the Scr.

The second disadvantage of the number of FTCs as criteria for risk of frost damage is that both a FTCs to -10°C at a saturation degree of almost 1 and a FTCs to -1°C and a saturation degree only slightly higher than Scr will be counted both as one FTCs, which is not in accordance with reality. In figure 1 can be seen that ice formation is even above the stated criteria highly dependent on the temperature and the saturation degree of the material. The third disadvantage is that the number of FTC in TRY's are quite small for mild climates which makes it difficult to analyse the proportion of potential risks.

The fourth downside is that the FTCs is very sensitive to seasonal climates that hover around 0°C [21] and of course this method still does not take into account or simplify some influencing parameters as salts [22], severeness of a FTCs [5], mechanical properties of the materials (e.g. tensile strength, extensibility and creep), pore size distribution and so on [7].

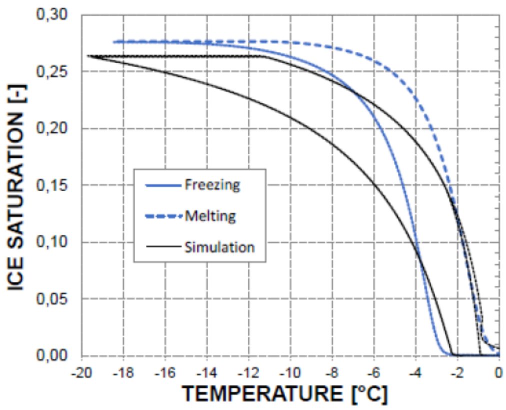


Figure 1 Comparison of the ice content vs temperature, obtained experimentally and from the simulations by] Koniorczyk M. [23]

The **winter index (WI)** is another damage function developed by Koci et al. [11] to assess the severity of a TRY in perspective to frost damage based only on climate data.

$$\mathrm{WI} = \sum_{i=1}^{8760} (\mathrm{T}_i - T_0)(RH_i - RH_0) \tag{2}$$

The WI is hourly calculated and dependent on the relative humidity and the temperature subtracted by their reference values. Koci suggests $\mathrm{T}_0 = 273{,}15$ K and $\mathrm{RH}_0 = 95\%$. Only when $\mathrm{T}_\mathrm{i} < \mathrm{T}_0$ and $\mathrm{RH}_\mathrm{i} > \mathrm{RH}_0$ the WI index is calculated. [11, 24] This index has the advantage that it takes into account how much the criteria's are crossed (figure 5).

The **Time-of-Frost (TOF)** is a similar damage function that counts only the hours in a year (bases on hourly data) that ice formation is possible, the criteria are assumed equal to these of the WI.. TOF can be expressed in hours or by % of the year [25].

$$\mathrm{TOF} = \sum_{\mathrm{i}=1}^{8760} \mathrm{if}(\mathrm{and}(T_i < T_0; RH_i > RH_0); 1; 0) \tag{3}$$

These last two criteria are developed to assess how severe a certain climate is in perspective to frost damage. Both are based on the ambient temperature and relative humidity. With the use of a HAM simulation program like Delphin, based on the theory of Grunewald [26] the effect of a climate on a real construction can be evaluated. As output 5 mm below the exterior surface the temperature, capillary pressure, moisture saturation degree and the relative humidity are assessed.

By using the saturation degree instead of the RH as input for the damage function the material properties can be taken into account. Of course the reference value is here the critical saturation degree here. This gives us these two new criteria.

$$\mathrm{WI_S} = \sum_{\mathrm{i}=1}^{8760} (\mathrm{T_i} - \mathrm{T_0})(\mathrm{S_i} - \mathrm{S}_{cr}) \tag{4}$$

$$\mathrm{TOF_S} = \sum_{\mathrm{i}=1}^{8760} \mathrm{if}(\mathrm{and}(T_i < T_0; S_i > S_{cr}); 1; 0) \tag{5}$$

The biggest advantage of the criteria WI and WIs is that the severity of temperature or saturation/relative humidity is taken into account. The higher the saturation/relative humidity above the reference value and the lower the temperature the higher the value for WIs or WI will be. But the temperature and saturation have an equal impact which is probably still not in accordance with reality [18]. Figure 1 shows experimental and simulation results of the ice formation in a fully saturated material [23]. We can see a non-linear ice formation with time and there are certain temperature limits. In this case at -1°C nothing happens and below -12°C everything is frozen. This indicates that it could be useful to develop in future research an index that caps off the WI and $\mathrm{WI_S}$ at certain temperature limits in future research.

So the phase change of water in porous building materials happens in a range below 273.15 K and not exactly at 273.15 K. The freezing temperature is dominantly influenced by the pore size distribution, the moisture content and the salt concentration of the material. As you can see on figure 1 there is even a hysteresis between freezing and thawing, this is caused by a different curvature of the water ice interface [25].

In “Crystallization in pores” Scherer defined these formulas that relate capillary pressure, pores size distribution and decrease in freezing temperature to each other [27].

$$p_c = p_l + \gamma_{cl}\varkappa_{cl} \tag{6}$$

$$\Delta T \approx \frac{\gamma_{cl}\varkappa_{cl}}{\Delta S_{fv}} \tag{7}$$

p_c	Capillary pressure	Pa
p_l	Liquid pressure =1atm	N/m²
γ_{cl}	Energy of the water/ice interface ≈0.04	J/m²
$\varkappa_{cl}$	Curvature of the crystal/liquid interface	1/m
ΔT	Change in phase changing temperature	K
ΔS_{fv}	Entropy of fusion per unit volume of crystal =1.2	J/cm³K

This gives

$$\Delta T \approx \frac{p_c - p_l}{\Delta S_{fv}} \tag{8}$$

This change in freezing temperature is implemented as T_0 in the previous indexes and the effect on the results is analysed.

Methodology

The Delphin simulations are rendered for a few varying input parameters. These parameters (table 1) are the climate, the wall assembly (no, thin or thick interior insulation) and the types of brickwork (high, average and low uptake speed/capacity). The wall orientation is always southwest because these are found as the most severe for frost damage.

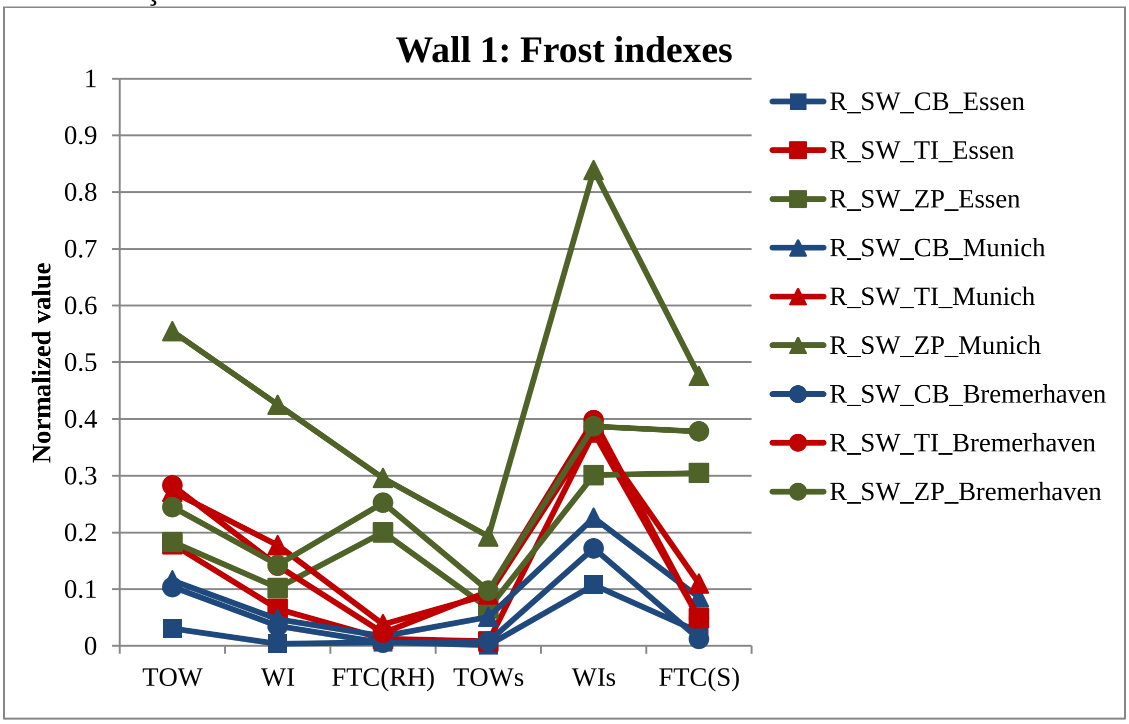
Brick types	Climate data	Setup
ID 513: Ceramic Brick (CB)	Essen (TRY)	Wall 1: Reference (19 cm brickwork)
ID 504: Old Building Brick Dresden ZP (ZP)	Munich (TRY)	Wall 2: Reference + 3 cm PU board (ID: 194)
ID 547: Old Building Brick Tivoli Berlin (outer brick 2) (TI)	Bremerhaven (TRY)	Wall 3: Reference + 12 cm PU board (ID: 194)

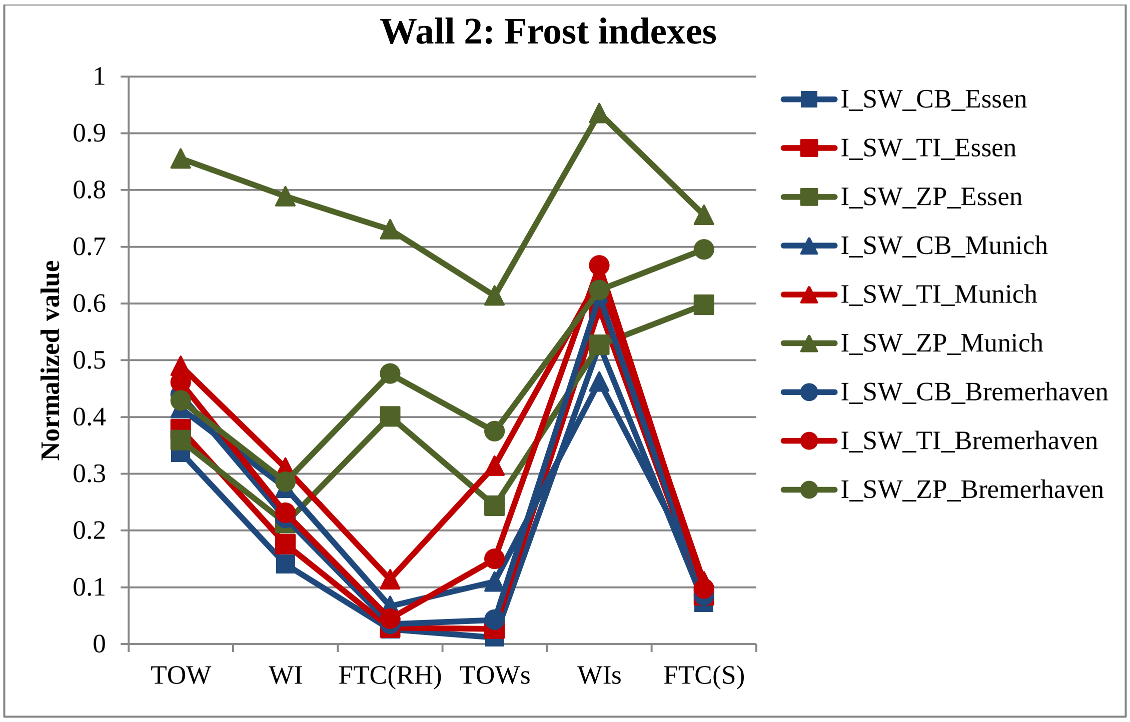
For each simulation the WI, WIs, TOF, TOFs, FTC (number of freeze thaw cycles for $RH_{act}>RH_0$), FTCs are calculated. The Scr is assumed to be 0.25 for the three brick types. All results are normalized by the maximum value found in the 54 simulations. This simplifies the comparison of results.

Results

In the not normalized values was found that the indexes using RH (RH_0=95%) usually define (at lower moisture contents) a risk of frost damage more quickly. This is as expected because the steep incline in the sorption isotherm in the overhygroscopic region of brickwork usually starts at higher RH values (figure 6). When it is known that the assessed exterior surface has a steep sorption isotherm as brickwork it is more suitable to choose a higher RH0 value, for example RH0=99%. The results for this high RH0 value will be a lot closer to the results based on saturation and will be more reliable.

Also as expected, all frost criteria show that wall configuration three is the most critical and configuration one is the least critical due to the decrease of/in drying potential and temperature in the exterior façade.





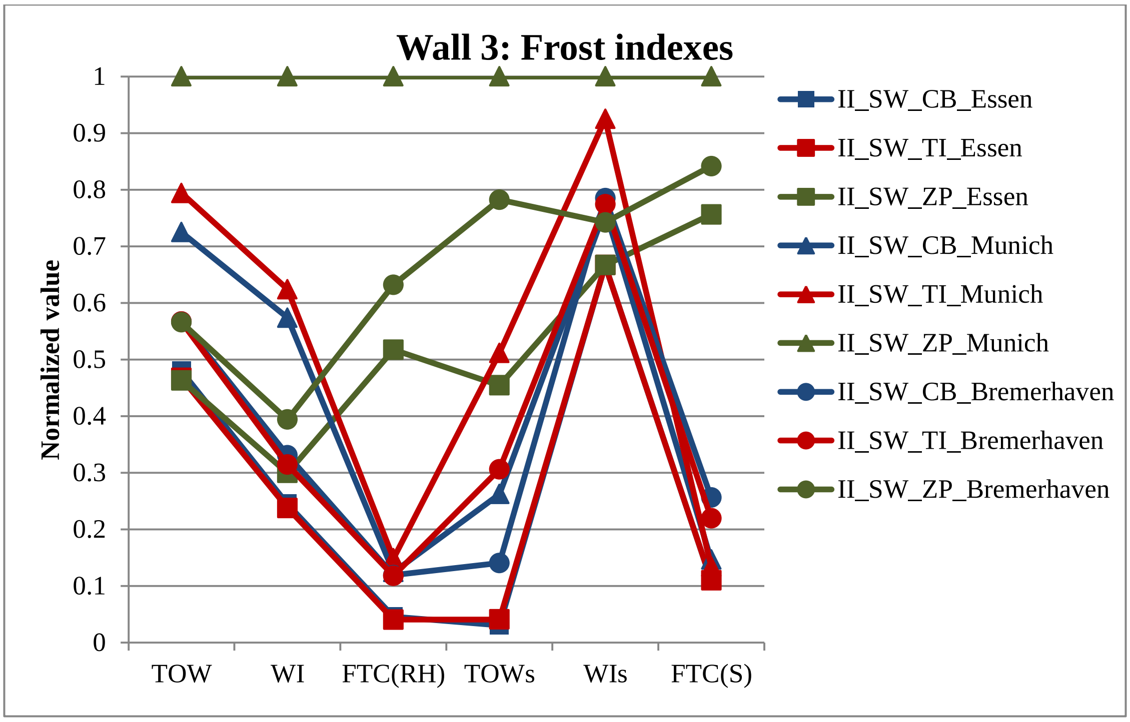


Figure 2-4 Wall 1-3: Normalized results of the different types of frost indexes

There can be noticed some tendencies in the results in figure 2-4. There is relatively no difference in the results of TOW and WI. This can be clarified because the RH and temperature are dependent parameters. This is not the case for TOWs and WIs, there the ZP type of brick is more vulnerable based on TOWs then on WIs. The TOWs is also the parameter that fits the best with the results based on the common frost indexes FTC and FTCs.

Most of the criteria define the ZP brick (green) as the most critical type of brickwork because of the low moisture storage capacity. This type of brick is for that cause very quickly saturated despite the low moisture uptake coefficient. This can be seen in figure 6.

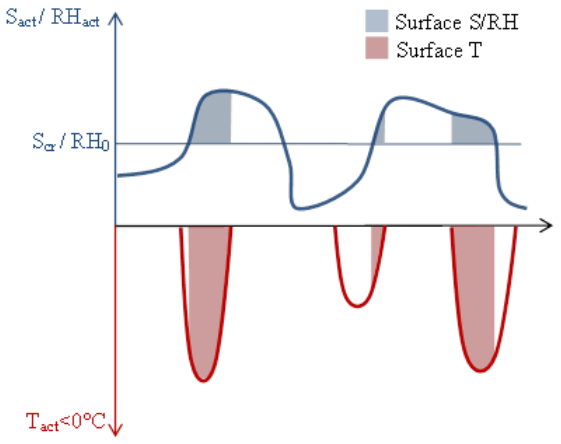


Figure 5 Principle of calculated surfaces

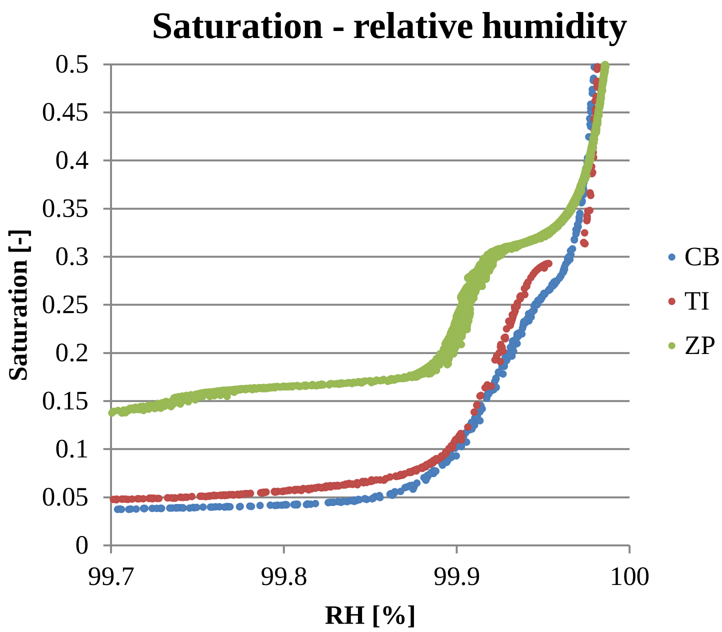


Figure 6 Sorption isotherm of the three brick types

The WI and WIs index seem promising indexes but one of their disadvantages is that they attach a similar importance to the temperature and to the saturation/relative humidity as can be seen in equation 2 and 4 while this is probably not the case in reality. Therefore the surfaces between the Scr and the Sact for T>273,15K (figure 3, blue) are plotted against the surfaces between T0 and Tact for Sact>Scr (figure 3, red). When the saturation and the temperature have an equal influence a linear relation between their normalized results should be found. The same calculations are made for the surfaces between the RH_0 and the RH_{act} for T>273,15K and the surface between T_0 and T_{act} for RHact>RH_0.

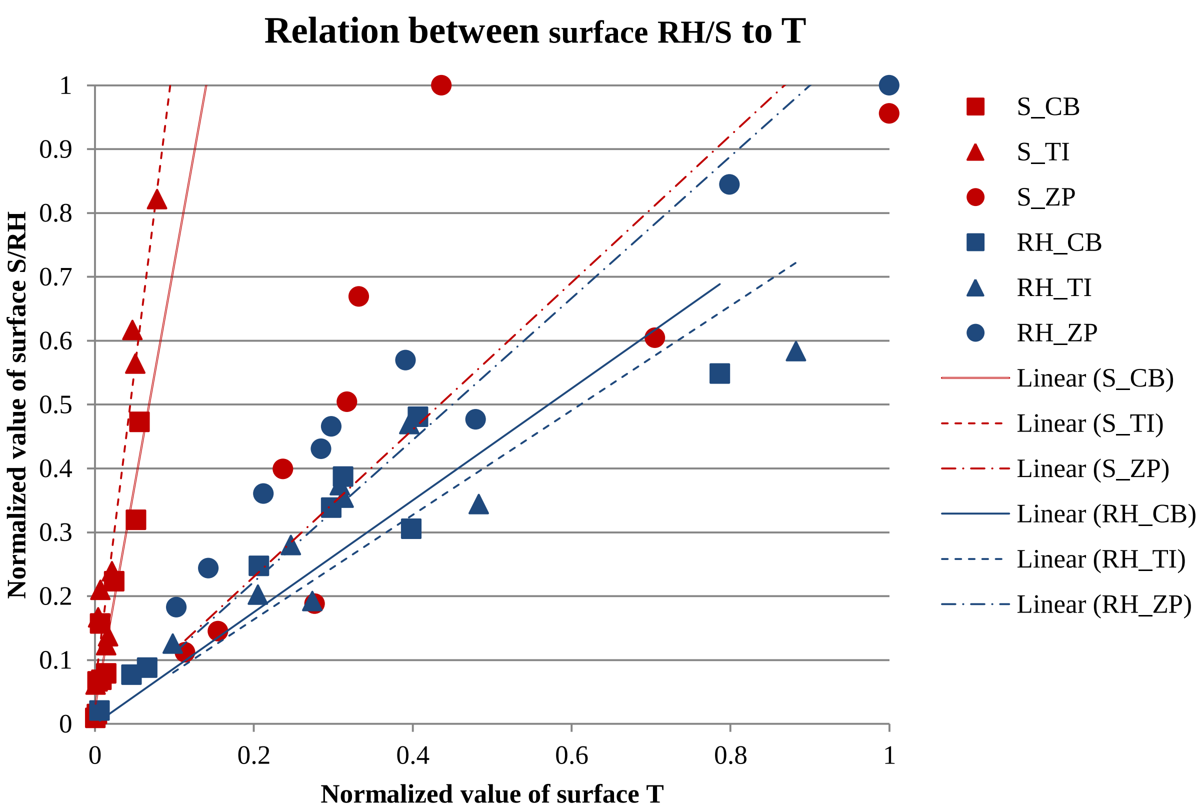


Figure 7 Influence of temperature and RH/S on the Winter index

For the assumed Scr= 0.25 and RH_0= 95%, the normalized surfaces are as given in figure 7.

The relation between the surface RH and surface T is more similar for the three types of brickwork than the relation between the surface S and surface T. This indicates that the lack of material dependent coefficients in front of equation 2 and 4 has a bigger influence on equation 4.

All values derived from the brick ZP (marked with dots) differ a lot from the result for the other two brick types this can be clarified by the different moisture behaviour as stated before (figure 6). Because brick type ZP is more quickly saturated, this leads to longer and more periods of saturated brickwork below freezing temperatures causing an increased influence of the saturation degree and a decreased influence of temperature on the WIs.

The use of lowered freezing temperatures (based on eq. 7), dependent on the capillary pressure in the pore structure gave only a small decrease in risk on all frost indexes so the use of a lower freezing temperature probably generates a more correct value but will not influence comprising results a lot .

Conclusions

Frost in porous material is a very difficult physical mechanism to numerically calculate. Therefore several indexes are developed from indexes specifying the severity of a climate to indexes based on the frost resistance of a specific material. Therefore this paper compares the most common frost indexes and some alternatives based on the output of HAM simulations.

This comparison gives insight in how big the influence of the chosen criteria (FTC, WI and TOF) can be on the assessment of frost damage. The WI based on saturation degree with the critical saturation degree as reference value seems a promising index for comparison of HAM simulation results.

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